Energy 35 (2010) 2752–2760

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Novel conceptual design of a supercritical pulverized coal boiler utilizing high temperature air combustion (HTAC) technology

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ARTICLE INFO

Article history:
Received 9 September 2009
Received in revised form
5 February 2010
Accepted 6 February 2010
Available online 10 April 2010

Keywords:
Boiler design
HTAC
MILD
Flameless oxidation
Coal combustion

ABSTRACT

Technical and ecological aspects of implementation of High Temperature Air Combustion to power station boilers fired with pulverized coal have been considered. Several boiler concepts have been examined in the context of the following three key points: existence of an intensive in-furnace recirculation, homogeneity of both the temperature and the chemical species fields, and uniformity of heat fluxes. CFD-based numerical simulations have been performed in order to determine the shape of the boiler and its dimensions, to optimize both the distance between burners and location of the burner block. It was concluded that HTAC technology could be a realizable, efficient and clean technology for pulverized coal fired boilers.

1. Introduction

Combustion technology provides more than 90% of our worldwide energy demand [1]. Severe environmental regulations and international agreements on reduction of pollutants emissions (CO_2, CO, NO_x, soot, particles etc.) raise a continuous demand for improved combustion technologies.

Coal is an abundant fuel resource in many of the developing regions and forecasts show that it is likely to remain a dominant fuel for electricity generation in many countries for years to come [2,3]. Coal-fired power plants currently generate approximately 40% of the world electricity. Since coal dominates the energy supply in the developing countries and still is an important fuel in the industrialized nations it will continue to play an important role in worldwide power generation [4,5]. The major challenge for the power generation industry is in increasing the power plants efficiencies and in meeting stringent environmental regulations. From the point of view of steam parameters, pulverized coal fired power plants can be divided into [6]:

- subcritical (under critical point of water[1]; usually 19 MPa and 535 °C)
- supercritical (over critical point of water; usually up to 24.1 MPa and 565 °C)
- ultra-supercritical (USC) (over supercritical conditions; usually 30 MPa and 600 °C)

In order to improve coal-fired power plant efficiencies the power industry must move from subcritical to supercritical steam cycles. A supercritical design not only improves the efficiency by increasing the working fluid pressure but it allows superheating of the steam to higher temperatures which provides a significant steam cycle efficiency improvement. Modern supercritical coal-fired power plants have efficiencies above 45%. The supercritical technology plays dominant role for the newly built power plants, however the installed technology is based predominantly on subcritical steam cycles.

High Temperature Air Combustion (HTAC or HiTAC) is named also as Excess Enthalpy Combustion (EEC), FLameless OXidation (acronym FLOX) or MILD (Moderate and Intensive Low-oxygen Dilution) combustion. The most important feature of HTAC technology is an existence of an intense recirculation of combustion products inside the chamber. This recirculation causes that both the combustion air stream and the fuel stream are diluted before the ignition occurs. Therefore, the temperature peaks are suppressed and both the temperature and the species concentrations fields are

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[1] The critical point of water is 22.06 MPa and 375 °C.

0360-5442/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.energy.2010.02.014

homogeneous. Consequently, HTAC technology features low NO_x and CO emissions and high and uniform heat fluxes. So far, HTAC technology was implemented mainly in industrial furnaces fired either with gaseous fuels or light oils [7]. In most of industrial furnace applications, the technology is combined with heat recovery systems and such a combination results in substantial fuel savings.

The main objective of this work is to investigate applicability of HTAC technology to power station boilers fired with pulverized coal for environmentally friendly electricity production with emphasis on supercritical operation.

2. Applications of HTAC technology in boilers

Although most of current applications are limited to industrial furnaces, HTAC technology is expected to provide significant advantages when applied also to power station boilers fired with pulverized coals. The foreseen advantages are as follows:

- An increase in radiative heat fluxes that may lead to a reduced size of the boiler
- More compact and smaller boilers can be built using a high quality steel so that the cycle thermal efficiency is improved due to increased (superheated) steam parameters
- A simple design of the burners and a very stable combustion process open up the possibility of using low rank coals
- Increased particle residence time is likely to improve char burnout
- The technology can be operated with a relatively low excess air
- The technology offers low NO_x emissions

A typical conventional boiler is composed of the radiative section and the convective section. An air preheater and an economizer are used to recover the waste heat of flue gases. In high temperature air combustion, the adiabatic flame temperature is much higher than that of a conventional boiler and the heat transfer inside the boiler is dominated by radiation. Thus, it should be possible to design a boiler without the convective section and yet maintain the same thermal output. The removal of the convective heat transfer region will certainly lead to a significant reduction of boiler size and cost. In Paragraph 3 we consider such a compact design.

In a coal or other fossil fuel fired boiler, it could be difficult to apply a honeycomb or ball regenerator, as it is typically done in furnace applications, since the fly ash would plug the regenerator. Power station boilers are usually of a large capacity and thus the flow rate of combustion air is significant. Preheating of such an amount of combustion air to a high temperature in a short time period is technically not easy. We realize that this important issue has to be addressed and resolved in the future. In this paper we focus on the combustion chamber design only.

Several authors have already postulated application of HTAC technology to power generation [8,9] but up to now there have been only two attempts [10,11] to apply this technology to power station boilers fired with pulverized coal. Kawai et al. [10] proposed a new concept boiler where a low BTU syngas derived from gasification process of coal and waste could be combusted in high temperature air. The boiler resembled an industrial furnaces equipped with regenerative burners. The compact boiler was characterized by: an uniform heat flux, an augmentation of heat transfer, a reduction of combustion noise level and a suppression of NO_x emissions.

Zhang et al. [11] proposed a boiler equipped with PRP burner (PRP stands for primary air enrichment and preheating). A low volatile petroleum coke and an anthracite coal were fired in an industrial scale (12 MWth) test facility and the PRP burner was installed at the side wall of the boiler. Besides the new burner construction no further modifications to the boiler were made. It was concluded that the PRP burner was able to create a two-stage hot gas recirculation inside and outside of the preheating chamber. The rapid heating of the combustible mixture in the chamber facilitated pyrolysis, volatile matter release processes for the fuel particles, suppressing ignition delay and enhancing combustion stability. Moreover, compared with the results measured in the same facility but with a conventional low-NO_x burner, NO_x concentrations at the furnace exit were at the same level when petroleum coke was used, and 50% lower when anthracite was fired.

3. Design of HTAC boiler

We embark then on a task of developing a conceptual 130 MWth boiler fired with Venezuelan Guasare coal. The boiler is meant to posses a radiative section only with its design and layout guaranteeing operation in MILD combustion regime. The boiler is to be equipped with unconventional but simple burners which can be

Table 1
The boiler design procedure.

Feature	Description
Boiler shape	Three shapes (A, B, C – see Fig. 1) have been considered; Section 3.1
Burner spacing	Configurations with five, three and one burner have been considered; Section 3.2
Burner Block Location	Up-fired and down-fired options have been considered; Section 3.3
Boiler Volume	Small, medium and large volumes have been considered; Section 3.4

Table 2
Features of the mathematical model used [12].

Sub-model	Description
Fluid flow	Eulerian description of gasphase; Lagrangian formulation for solid phase; $k-\epsilon$ turbulence model
Turbulent combustion	Eddy Dissipation Concept for turbulent combustion; two global reactions for volatile matter combustion
Combustion of Guasare coal	Detailed modeling based on comprehensive fuel characterization experiments
NO_x post processor	Fuel, Prompt and Thermal NO included
Radiative Heat Transfer	Discrete Ordinates method with experimentally determined absorption coefficient

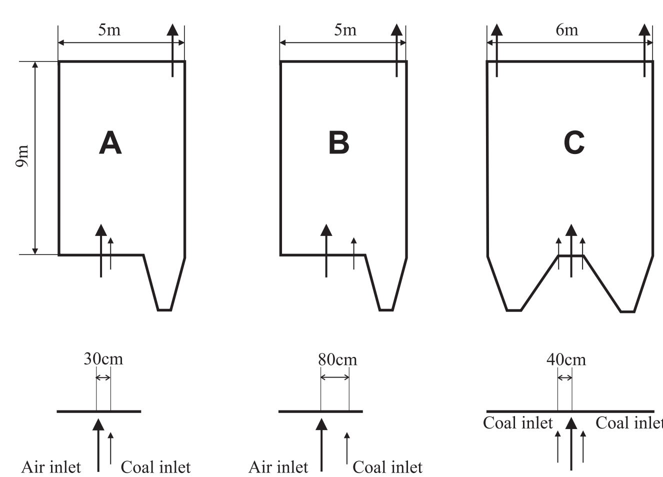

Fig. 1. Illustration of the considered combustion chamber forms with 30 cm distance, with 80 cm distance and symmetric configuration.

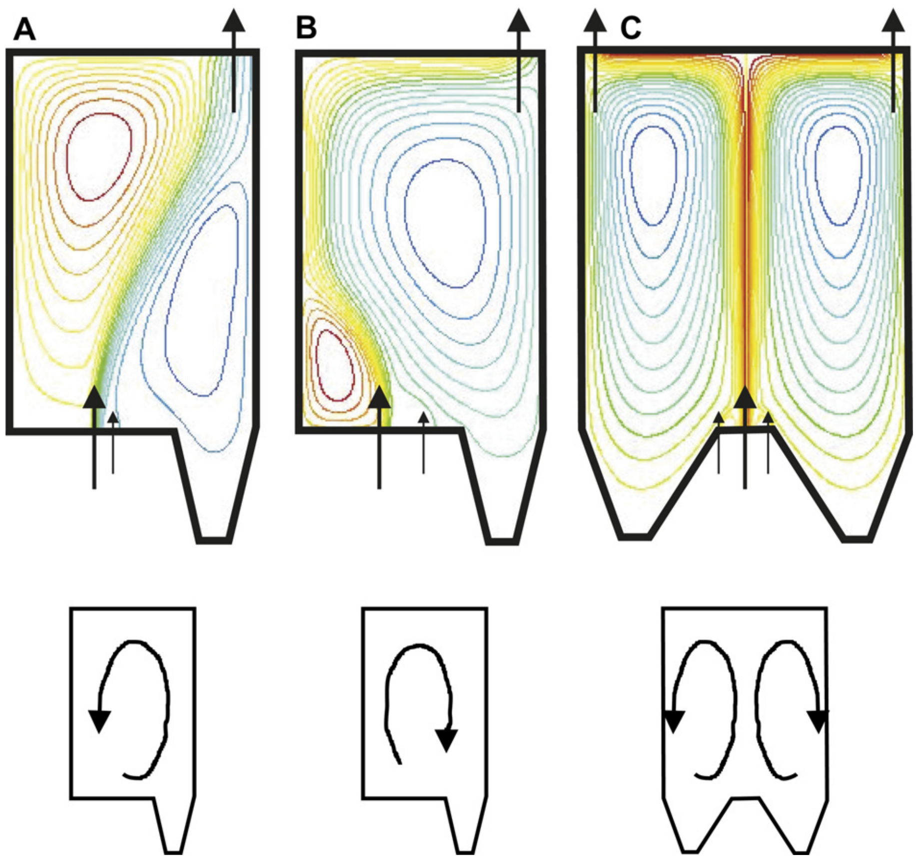

Fig. 2. Predicted recirculation zones inside the combustion chamber.

characterized by a high momentum (strong) central (combustion air) jet and two (weak) coal jets [12].

The boiler design procedure consists of the steps outlined in Table 1. Several boiler concepts are analyzed in the context of the following three key points: existence of an intensive in-furnace recirculation, homogeneity of both the temperature and the chemical species fields, and uniformity of heat fluxes. Numerical simulations have been performed in order to determine the shape of the boiler and its dimensions, to optimize both the distance between burners and location of the burner block. To this end a CFD-based mathematical model has been developed and validated. The model has been comprehensively described in our accompanied paper [12] and the main features are listed in Table 2.

3.1. Boiler shape

The first challenge of this work is to find a shape of the boiler appropriate for HTAC technology. Calculations have been performed for three different boiler shapes which are marked in Fig. 1 as designs A, B and C. The first two (A and B) designs are derived so as to resemble standard PC boilers. The third (C) boiler is an innovative concept of the authors, invented to create a proper internal recirculation of the combustion products.

As shown in Fig. 2, the geometry of the boiler and the configuration of the inlets determine the recirculation pattern inside the boiler. The intensive recirculation created in the symmetric boiler results in a more uniform temperature field, lower temperature peaks, moderate oxygen concentrations, and complete burnout of the combustible gases and the char. Table 3 lists the calculated peak temperature and burnout for designs A, B and C. The table lists also standard deviations of the predicted temperature and oxygen fields. The lower values for design C indicate the highest degree of homogeneity. As a result of the simulations, the symmetric boiler has been found to be the most suitable among the three considered designs, so further work focuses on this concept.

3.2. Distance between individual burners

The interaction between the burners and the combustion chamber is very important in HTAC technology. An optimization of the distance between the burners and its relation to the combustion chamber is the goal of the second calculation series. Three different configurations of the burners are tested: a boiler with five burners, a boiler with three burners, and a boiler with one burner only, as shown in Fig. 3.

It was observed that the distance between single burners affects the mixing conditions inside the boiler, especially the air and the fuel jets dilution with the combustion products. The single burner boiler produces unsatisfactory global recirculation while the boiler with five burners features insufficient entrainment (see Fig. 4 and Table 4). Therefore for further investigations the burner spacing of 1.5 m is chosen and five burners are used in order to keep the thermal input of 130 MWth.

Table 3
Results of the boiler shape determination.

	A	B	C
Peak temperature, K	2618	2437	2106
Burnout, %	97	99	100
Standard deviation of the temperature, K	375	238	290
Standard deviation of the oxygen concentration, %	3	5	1

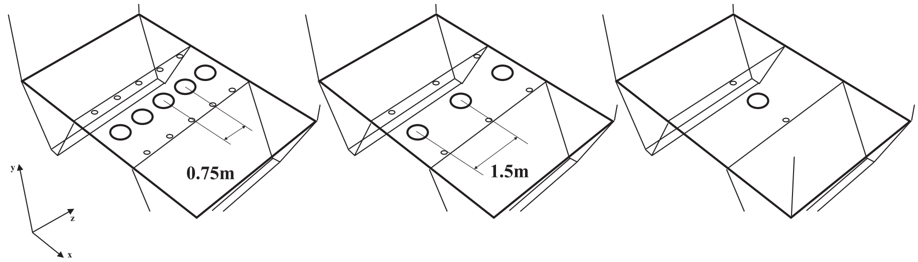

Fig. 3. Geometry of the examined boilers: with five burners (left), with three burners (center) and with one burner (right).

3.3. Location of the burner block

The third simulation series has been carried out to examine the down-fired configuration of the HTAC boiler and to compare the results with the up-fired one. The down-fired configuration has been tested because of slagging problems and a risk of the burner destruction by the agglomerated ash, when the burner is located at the bottom. Several advantages of the down-fired boiler have been identified; the recirculation path is longer in the down-fired configuration than in the up-fired one resulting in a more intensive heat transfer (see Fig. 5 and Table 5). So, lower flue gas temperatures are observed. Furthermore, the down-fired configuration features more uniform heat fluxes. Therefore, the down-fired configuration has been selected for further investigations.

3.4. Dimensions of the boiler; boiler size

One of the most important advantages of HTAC applications are high heat fluxes. Thus, compact combustion chambers can be built and the investment costs can be lowered. The fourth calculation series was carried out in order to find the combustion chamber dimensions which can, on one hand, ensure an efficient heat exchange between combustion gas and water/steam mixture and on the other hand, ensure high values of firing density. Three different sizes are tested and they are named in Fig. 6 as the small boiler, the medium size boiler and the large boiler. It has been observed (see Fig. 7 and Table 6) that the small boiler is too short. At the top a region of high temperatures exists and its enthalpy cannot be efficiently used. To the contrary, in the large boiler although the heat fluxes are uniform, they are two times lower than in the medium size boiler. Therefore, the medium size boiler configuration is chosen for further investigations.

4. Final configuration of the HTAC boiler

Based on the previous investigations, the final configuration of the HTAC boiler was selected and it is presented in Fig. 8. The boiler is 13 m high and has a 7 m times 6 m cross-section. It is equipped with a burner block that consists of five identical burners located at the top wall; thus the boiler is a down-fired one. The flue gas 1 m $\times$ 1 m square outlets are also located at the top and they are symmetrically positioned on both sides of the burner block. Each of the five burners is equipped with a central injector of hot air and two coal guns positioned on both sides of the air injector. Pulverized coal is introduced into the furnace by nozzles of 140 mm diameter and the combustion air by 480 mm nozzles. The boiler is equipped with two ash hoppers. The combustion air is preheated to 1200 K and the coal together with its transport air is supplied at ambient temperature (300 K). The coal feeding rate is 3.2 kg/s, and its transport air is almost twice as high. The mass flow of combustion air is equal to 33.1 kg/s. The air jet is supplied at a high velocity (120 m/s) and the coal jet has the velocity of 30 m/s. The boiler is operated at 130 MW total thermal input. The fuel thermal input is equal to 100 MW so each burner operates at 20 MW fuel power. Both the combustion and the transport air streams contain 23% (wt) oxygen and 77% (wt) nitrogen. The wall temperature is constant in the final boiler design calculations and it is equal to 800 K.

The final boiler design possesses an intensive in-furnace recirculation and the dead zones are small, as can be observed in Fig. 9. The whole volume of the chamber participates in the combustion process. The internal recirculation of the combustion products creates homogenous both the temperature and the chemical species concentration fields. Further, due to the dilution of the combustion air and fuel jets with the combustion products, coal ignition takes place in low oxygen concentration environment, and therefore the temperature peaks are suppressed.

The whole boiler is filled up with combustion products of 1600–2000 K temperatures while the furnace exit temperature is around 1400 K. As mentioned in Paragraph 2, a means of using the exit gas enthalpy to preheat the combustion air must be developed. This enthalpy must be recovered in a heat exchanger and utilized to preheat the combustion air. The oxygen concentration in the entire boiler is in a range of 3–5% while in the flue gas is equal to 3.4%. As a result of the strong recirculation inside the combustion chamber

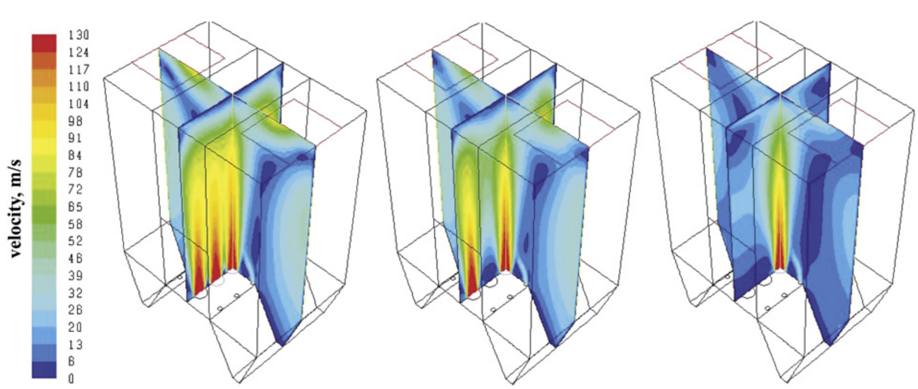

Fig. 4. Velocity contour in a boiler equipped with five burners (left), with three burners (center) and with one burner (right).

Table 4
Results of the burner distance determination.

	Five burners	Three burners	Single burner
Temperature peak, K	2017	1874	1660
Standard deviation of the temperature, K	250	150	112
Recirculation, %	22.20	20.21	12.85

and as a consequence of the uniform temperature field, the heat fluxes are high and almost constant along the height of the HTAC boiler (see Fig. 10, right). For the sake of comparison typical heat flux profiles for fluidized bed boilers (see Fig. 10, left [14]), and conventional wall fired boilers (see Fig. 10, center [14]) are also shown. The HTAC boiler has two advantages: uniform heat fluxes along the boiler height (as in fluidized bed boilers) and high heat fluxes values (as in wall fired pulverized coal boilers). Heat transfer due to radiation is dominant; its share is 83% of the total heat transfer rate.

4.1. Environmental issues

Most of NO is generated in the region between the burners. The NO concentration peak is equal to 1195 ppm. Downstream of this region the nitric oxide concentrations are low and they are in a 300–400 ppm range. In the HTAC boiler, 98% of nitric oxide is formed via fuel mechanism and the NO reburning mechanism plays an important role. As a result, the nitric oxide concentrations at the boiler outlet are low and equal to 298 ppm (For a detailed discussion of the NO_x formation and destruction mechanisms the reader is referred to [12]). The long particles residence time and recursive recirculation of the combustion products improve the burnout of the CO, volatiles and the char (see Fig. 11). This very stable combustion process and simple burner construction offer the possibility of using low rank coals.

Table 5
Results of the burners location determination.

	Up-fired	Down-fired
Heat transfer rate, kW/m^2	220	261
Outlet temperature, K	1722	1568

5. Effects of selected operating parameters

Impact of three important parameters: the combustion air preheat, the combustion air jet velocity and the air excess ratio on the HTAC boiler performance is examined. For all calculations of Paragraph 5, the final HTAC boiler geometry is retained and the same boundary conditions are applied. However, boiler operating conditions are different and these are specified for each computational run. The final boiler design presented in Paragraph 3 serves here as the reference case.

5.1. Impact of the combustion air preheat

The possibility of operating the HTAC boiler using the ambient temperature air (300 K), 600 K air preheat and 900 K air preheat are examined in this calculation series. The fuel input is kept constant for every simulation and it is equal to 100 MW. However, the total load of the boiler decreases due to a decrease of the combustion air temperature. The combustion air which is preheated to 1200 K has the enthalpy of 30 MW. The numerical simulations show that HTAC technology can be also realized without preheating the combustion air stream. The essential features of HTAC technology: a strong combustion products recirculation, dilution of the combustion air and fuel, uniformity of both the temperature and the species concentration fields and low temperature peaks, are obtained for each examined combustion air temperature. However, with a decrease of the combustion air temperature and a subsequent decrease of the thermal input, the temperature level inside the boiler

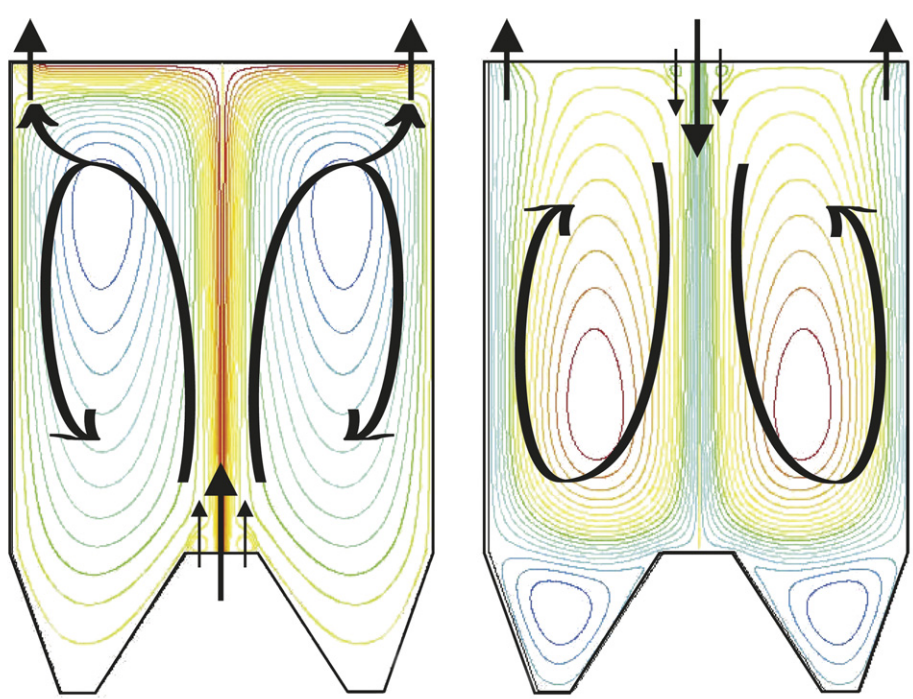

Fig. 5. Recirculation inside the up-fired boiler (left) and down-fired boiler (right).

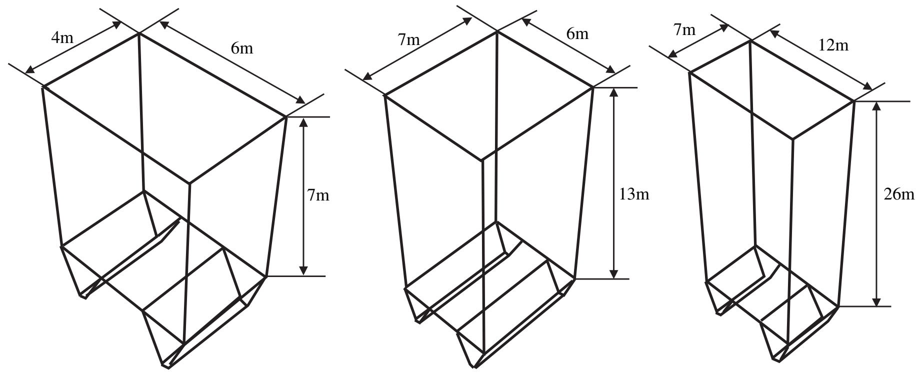

Fig. 6. Geometry of the examined boilers: a small boiler (left), a medium size boiler (center) and a large boiler (right).

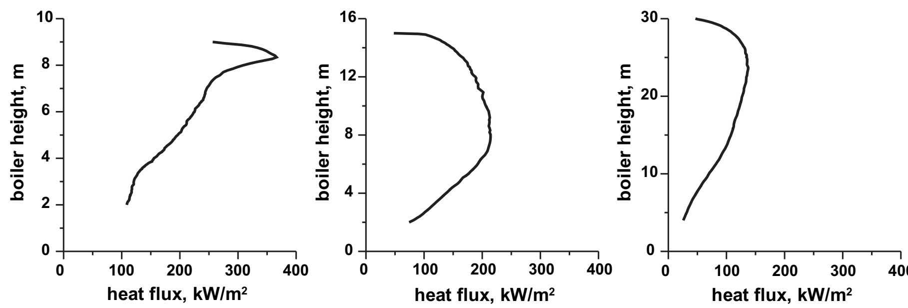

Fig. 7. Heat fluxes along height of the boilers: a small boiler (left), a medium size boiler (center) and a large boiler (right).

also decreases. It can be concluded that the combustion air temperature has little impact on the performance of the HTAC boiler providing that the intensive in-furnace recirculation has been created. Therefore, the HTAC boiler can be operated with different levels of air preheat.

5.2. The HTAC boiler equipped with low-momentum burners

The key issue of the HTAC technology is a high velocity (a high momentum) of the central air jet. This creates an intense in-furnace recirculation which provides uniformity of all field variables inside the combustion chamber. Such high inlet velocities required powerful blowers consuming significant amount of electricity. Therefore, in this simulation series a possibility of operating the HTAC boiler with a low velocity central air jet (60 m/s) is examined. It has been confirmed (see Fig. 12) that a high velocity of the strong combustion air jet is essential to create an adequate recirculation pattern inside the combustion chamber. If this injection velocity is reduced by half, the recirculation is not intensive enough. Both the combustion air and the fuel jets are not diluted by the combustion products and as a consequence, the important characteristics of the HTAC technology disappear: the homogeneity of both the temperature (see Fig. 12, left) and the oxygen concentration fields (see Fig. 12, right), low temperature peaks and uniformity of the heat fluxes profiles along the height of the boiler.

5.3. The HTAC boiler operated at nearly stoichiometric conditions

One of the important factors controlling combustion in a boiler chamber is an amount of the supplied air. Operating a boiler with a too low air excess results in incomplete combustion. On the other hand, a too high air excess ratio results in an excessive outlet loss. In this calculation series the possibility of the boiler operation at low air excess is examined. The oxygen concentration level is higher in the boiler operated at $\lambda = 1.2$ than in the boiler operated at $\lambda = 1.05$. However, the oxygen concentration is high enough to obtain a complete coal burnout. In the HTAC boiler, the coal particles residence time is extended due to the intensive recirculation of the combustion gas. Therefore, one expects that char burnout problems are minimized. This opens up the possibility to operate the HTAC boiler at a low air excess ratio.

6. Steam cycle

Boiler design procedures involve an examination of the combustion process as well as the steam cycle. Both issues are strongly coupled due to the heat transfer proceeding from the combustion products inside the chamber to the water/steam mixture inside the boiler tubes. In this simulation series the coupling between HTAC boiler and the entire steam cycle is considered. The final boiler geometry as well as the operating and boundary conditions are the starting point for these calculations. The algorithm describing the calculation procedure is schematically shown in Fig. 13. The heat transfer rates per unit of height ($\dot{Q}_l$) of the membrane wall have been obtained in the CFD predictions of the combustion chamber. This heat is transferred to the boiler tubes and to the working fluid. The heat conduction through the tube walls is neglected. At the beginning of the process the working fluid is a supercritical water which is then converted into an ultra-superheated steam. The working fluid consists of the one phase only because of supercritical conditions of the process.

Table 6
Results of the burner distance determination.

	Small boiler	Medium-size boiler	Large boiler
Firing density, kW/m^3	774	238	59
Outlet temperature, K	1805	1558	1299

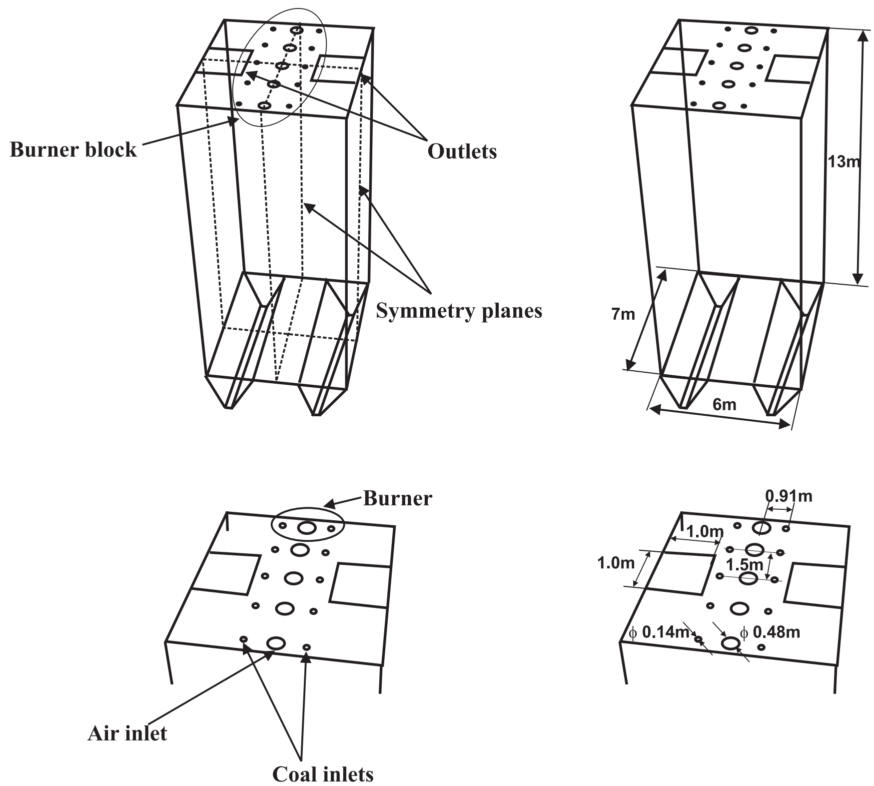

Fig. 8. Final geometry of the HTAC boiler.

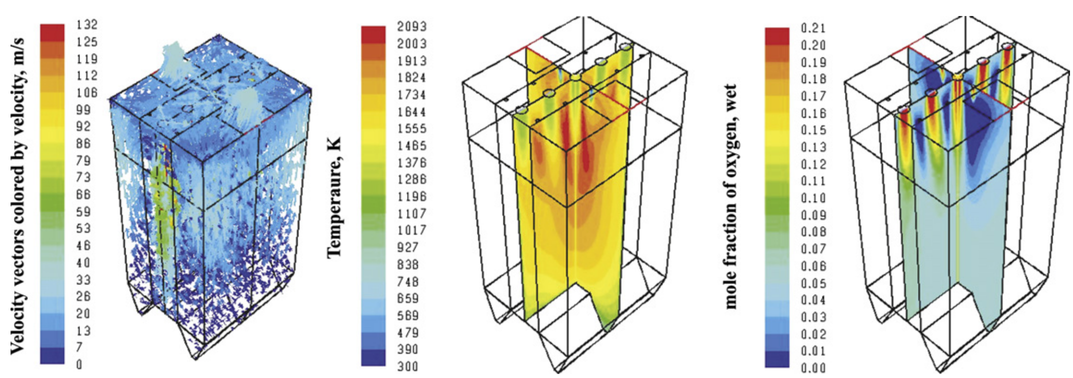

Fig. 9. Velocity vectors (left), temperature field (center) and oxygen concentration field (right) inside the HTAC boiler.

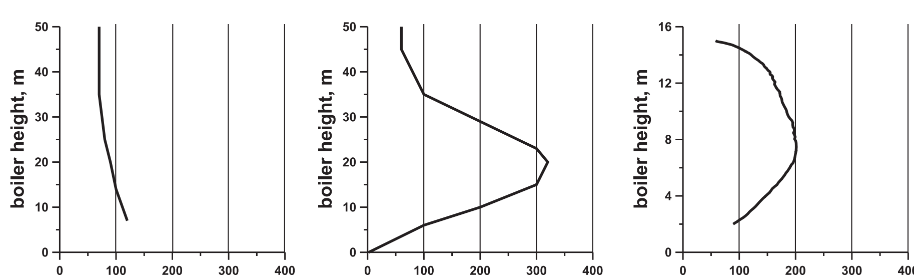

Fig. 10. Heat fluxes along height of a fluidized bed boiler (left) [14], conventional pulverized coal boiler (center) and the simulated HTAC boiler (right) [14].

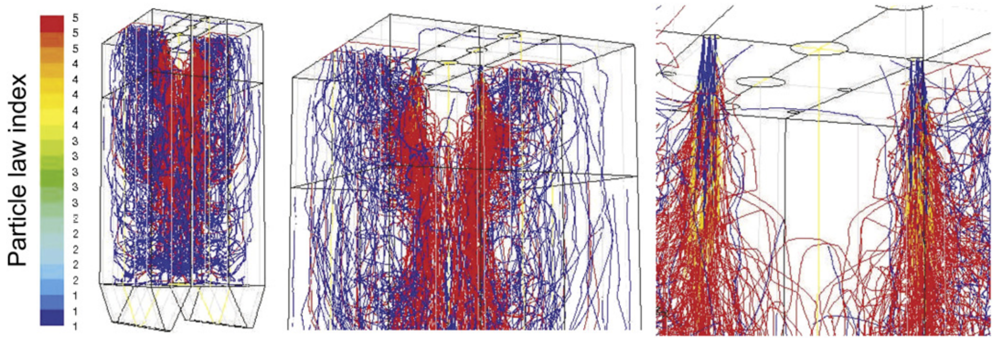

Fig. 11. Char burnout regions inside the HTAC boiler.

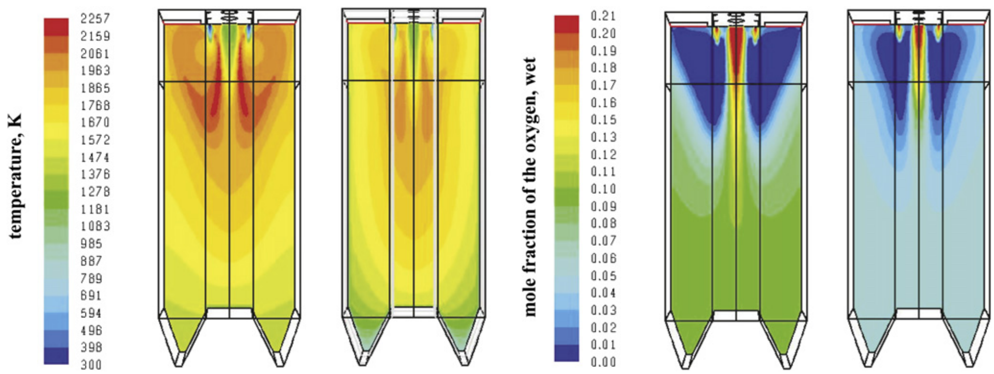

Fig. 12. Boilers with 60 m/s and 120 m/s combustion air inlet velocity: temperature field inside the boilers (left) and oxygen concentration field inside the boilers (right).

The heat transfer rate between the combustion products and the working fluid is described by the following equation:

$$\frac{d\dot{H}}{dy} = \dot{Q}_l \tag{1}$$

introducing into the above equation the mass flow of the medium one obtains:

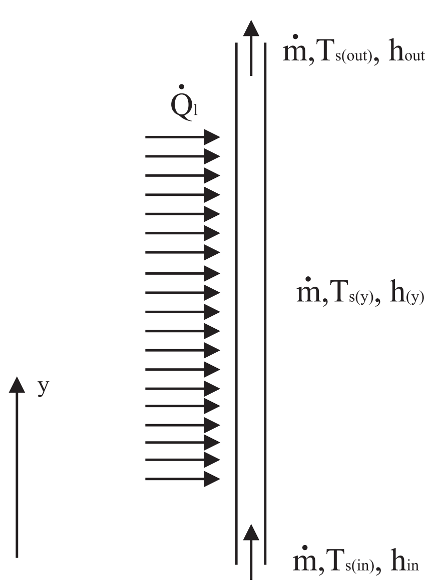

Fig. 13. Algorithm for the boiler tube heat transfer calculations.

$$\dot{m}\frac{dh}{dy} = \dot{Q}_l \tag{2}$$

where $\dot{Q}_l$ is the heat transfer rate per meter of the tube height, $\dot{H}$ stands for the total enthalpy rate of the medium, h is the medium specific enthalpy and $\dot{m}$ is the mass flow rate of the medium while y is the distance in y direction (see Fig. 13).

Using Eq. (2) the specific enthalpy of the medium, represented by $h(y)$ is calculated, as a function of y distance. Furthermore, the temperature of the working fluid, denoted as $T_s(y)$ is calculated using the steam tables. This temperature should be lower than 750 °C which is assumed in this calculations as the maximum allowable temperature of the steel material. The steam pressure is assumed to be $p = 30$ MPa and water/steam mass flow is equal to 17 kg/s. Additionally, the convective heat transfer coefficient α is computed along the tube at the side of the supercritical working fluid. The Nusselt function is calculated for the water/steam under supercritical conditions according to the formula of Yamagata et al. [13]. The efficiency of the fins is assumed to be equal to 1. As a result of these calculations, the temperature profiles at the boiler walls are obtained. The HTAC boiler is proposed as an ultra-supercritical boiler with the once-through type of the water circulation. Three commonly used configurations of the once-trough boiler tubes were tested in this series of calculations: vertical down-up, up-down and spiral (see Fig. 14, top).

The most uniform temperature profile can be found in the boiler with the spiral tubing as can be found in Fig. 14, bottom. Comparing the two vertical tubes arrangements, it can be noticed that the up-down configuration works worse than the down-up one. It was concluded that the spiral tubes configuration is the most suitable for the HTAC boiler designed in this work. However, this configuration is technically most complicated. The Rankine cycle efficiency of the

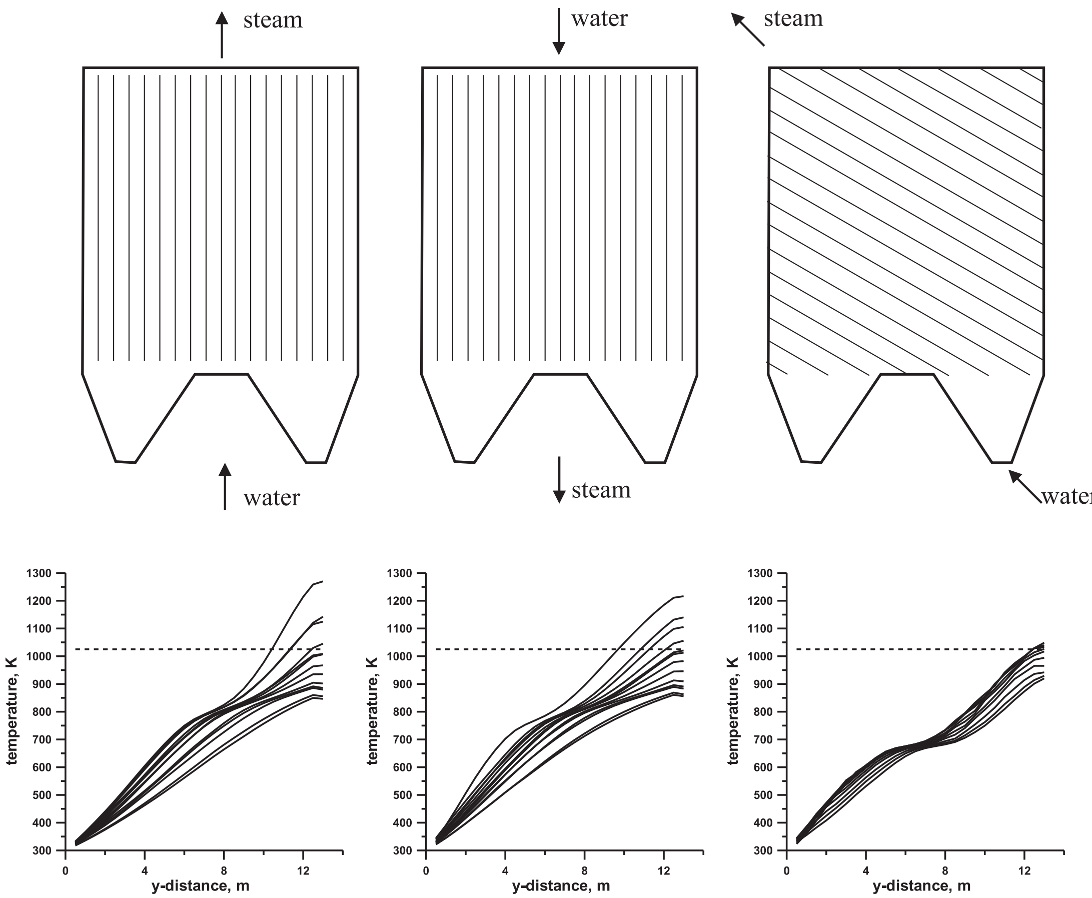

Fig. 14. Heat flux along the height of the boiler for the simulated tubes arrangements: vertical down-up (left), vertical up-down (center) and spiral (right).

steam cycle coupled with the HTAC boiler is calculated to be above 50%.

7. Conclusions

The present study has confirmed that HTAC technology can be a realizable, efficient and clean technology for pulverized coal fired boilers. The most important advantages of the pulverized coal fired boiler operating under HTAC conditions are as follows. Firstly, the heat fluxes are high and uniform. Secondly, low NO_x emissions are expected in comparison with standard PC boilers. The conceptual 130 MWth boiler design for supercritical operation features the radiation section only. It is equipped with five burners of a very simple construction; neither air staging is used nor flame stabilizers (no bluff body, no swirl) are applied. It has been demonstrated that the momentum of the combustion air stream is an essential design parameter driving the in-furnace recirculation; a too low air jet momentum is likely to compromise the boiler performance. The study also shows that the impact of the combustion air temperature on boiler performance is less critical providing that the intensive in-furnace recirculation has been created.

Acknowledgments

The work has been carried out within the European Commission Marie Curie INSPIRE Network (MRTN-CT-2005-019296) and the Project of Polish Ministry of Education and Science (2908/T02/2007/32). The authors acknowledge with thanks the financing.

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